Final Report

Efficient Laser Ablation -Project AOARD 044033

Shigeaki Uchida

Tokyo Institute of Technology, Integrating Research Institute

Also at Institute for Laser Technology

Introduction

This report deals with the problems of applying phenomena of laser-matter interaction to generating propulsive force in space. The advantages of using laser is that it can avoid use of explosive or toxic oxidizing chemicals and eliminate the necessity of high voltage power supply that is for electrical propulsion systems. To use the most out of the advantages of laser propulsion, laser should be powered by solar radiation through solar cells, therefore the early stage of its development most likely will start with small power system. Feeding system for propellant is one of the crucial elements of the development of such system. A scheme using solid state propellant has been proposed by Phipps where polymer tape is irradiated to generate thrust while being fed by a rotating reel. However, this system is the first demonstrated system of laser propulsion system, the most of the mass on the tape is not used as propellant and thus the mass efficiency of propellant is not good since only tiny area on the tape surface is irradiated by laser pulses. The present report, instead proposes a scheme of using liquid propellant. The report is divided into two parts; the first part is devoted to the characterization of laser interaction with liquid in terms of impulse generation, and the second part describes one of the feeding scheme of the propellant.

CO_2 laser has been chosen as a laser source, since its wavelength is well absorbed by many kinds of liquid especially with O-H bonding. This choice results in a strong deposition of laser energy within a thin surface layer of propellant leading to large specific energy, energy absorbed by a unit mass of propellant, and relatively high specific impulse. Pulsed format of temporal profile of laser radiation has been also chosen for the purpose. Repetitive Q-switched pulses were used in the experiments to achieve significant propellant heating with moderate amount of average laser power. The first part of the report describes the characterization of several propellant materials in terms of performance of thrust generation with given amount of laser energy.

Feeding mechanism of propellant is one of the most important technical items for a

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14. ABSTRACT
This projects deals with problems of applying phenomena of laser-matter interaction to generating propulsive force in space. The advantages of using laser is that it can avoid use of explosive or toxic oxidizing chemicals and eliminate the necessity of high voltage power supply that is for electrical propulsion systems. The present report proposes a scheme of using liquid propellant. CO2 laser has been chosen as a laser source, since its wavelength is well absorbed by many kinds of liquid especially with O-H bonding. Pulsed format of temporal profile of laser radiation has been also chosen for the purpose. Repetitive Q-switched pulses were used in the experiments to achieve significant propellant heating with moderate amount of average laser power. It can be concluded that use of porous plate for feeding liquid propellant is possible. Several operating and designing parameters such as porosity, feeding pressure, propellant viscosity and vapor pressure, laser pulse repetition rate have to be optimized for the best performance of the system. Matching of the laser wavelength and absorption coefficient of propellant is also an important factor. It was found that realistic choice of these parameters is possible within reasonable range of physical value

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propulsion system. Laser propulsion system requires a sheet like structure to its propellant at the laser irradiation position, therefore the liquid propellants need to be fed in a form of thin layer of liquid. This report proposes a scheme of propellant feeder that uses a porous material. A basic characteristics of the principle was investigated and described in the second part of the report.

Liquid propellant characterization

Experimental setup

The experimental setup is consists of two parts, laser system and impulse measuring system. The laser system generate high peak power of infrared radiation to give ablation of the surface of the propellant. The impulse measuring system consits of propellant target attached with a piezo electrical device for impulse measurements.

Laser system

The setup of the laser system is depicted in Figure 1. Transversely Excite Atmospheric Pressure Carbon Dioxide (TEA CO_2) laser was employed for the experiments. The laser system is equipped with a Q-switch that generates 60 ns pulse with peak output power of 20 MW (Pulse energy is 1 J). The system can be operated at 1-Hz repetitive mode. Laser pulse is triggered by an external signal that is also used to trigger oscilloscope.

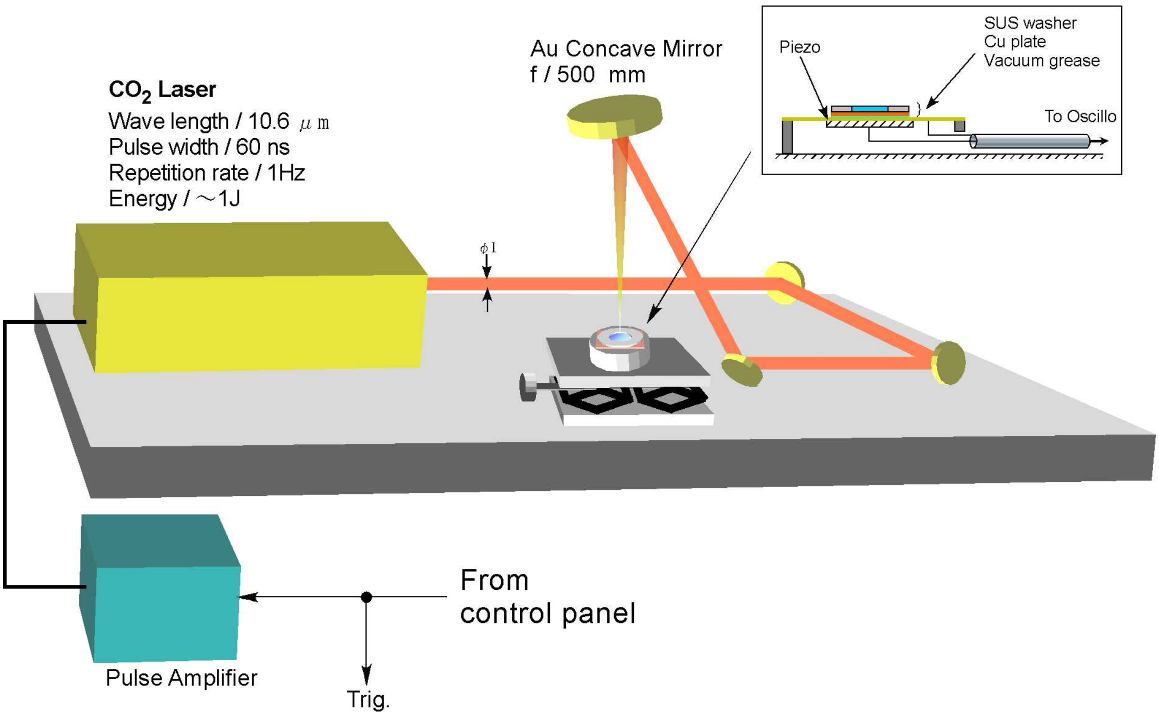


Figure 1 Laser setup

Pulse energy of laser is altered by inserting two beam splitters (BS) made of Zinc

Selenide, ZnSe that gives 8% reflection on each surface. To avoid beam shift due to inserting BS, the incident angles of the BS are set to be nearly 0 (in the case of single BS) or 45% (in the case of two BS) as shown in Figure 2. Some of the reflections were used to measure pulse energy and to obtain first triggering time through a photon drag detector.

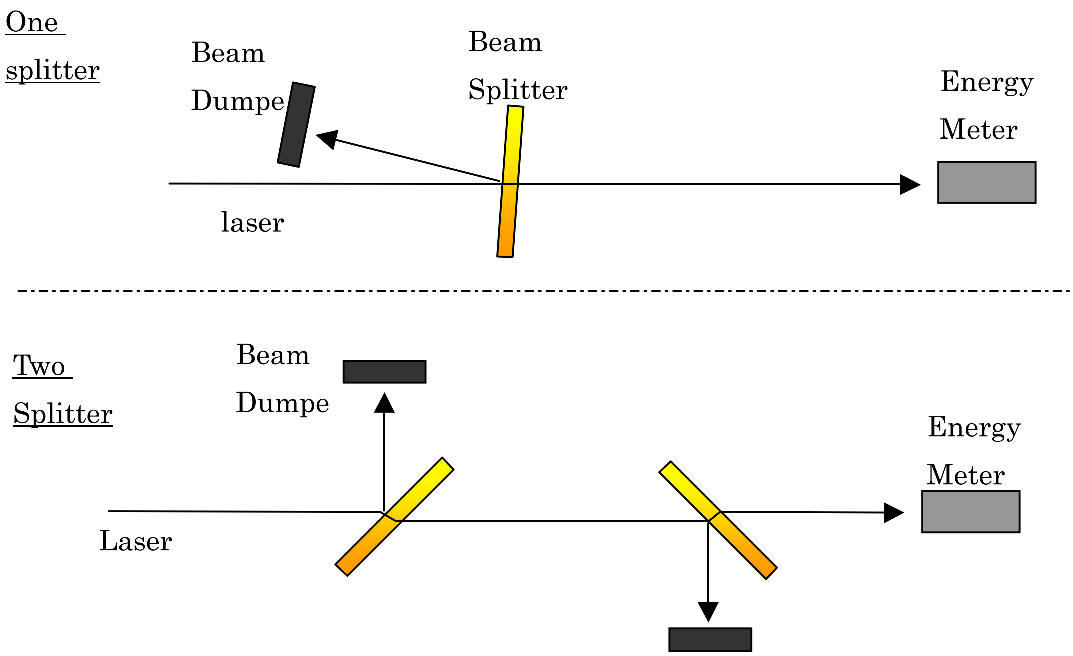


Figure 2 Setup of energy controlling system using ZnSe beam splitter

Impulse measurement system

The thrust generated by laser pulse irradiation on a liquid surface was measured by a Piezo electric plate. This device is very cheap and yet can be used to measure absolute value of thrust when calibrated with a known impulse generator. The schematic of the measuring device is shown in Figure 3. The piezo device generates voltage signal that is proportional to its distortion. Since the distortion is considered to be proportional to force exerted on the plate, the temporal profile of the piezo plate is proportional to the instantaneous force exerted on the device. The output signal was recorded with a digital oscilloscope.

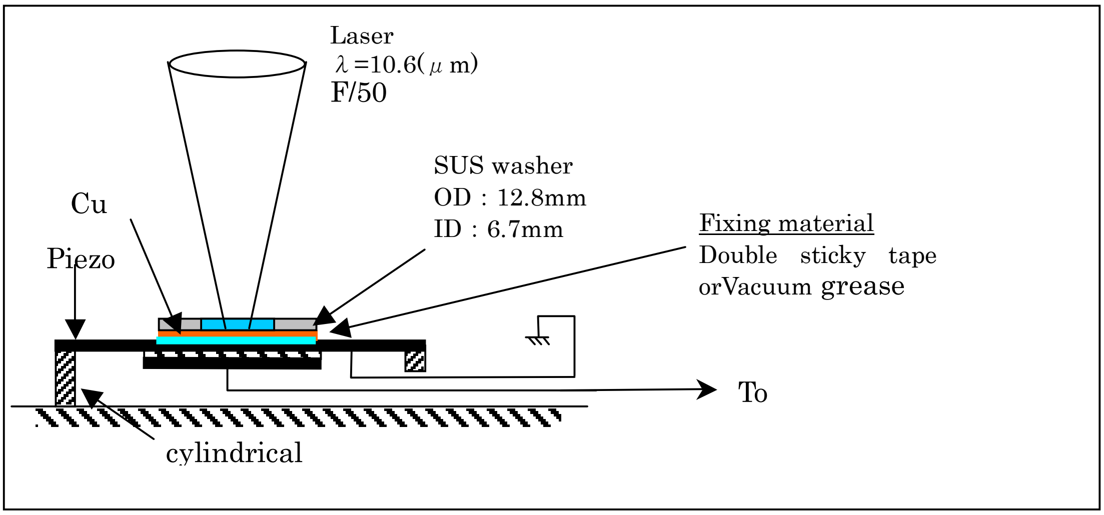


Figure 3 Experimental setup for thrust generated on liquid propellant

Liquid propellant was placed on a cupper square plate of 13 mm wide. A stainless steel washer was attached on the plate to hold liquid propellant. The cupper plate was interface with the piezo plate either by double sticky tape or vacuum grease. The effects of these methods on thrust measurements were checked before the experiments and confirmed that there were no significant effects on the measurements as shown in Figure 4. This check was done by irradiating only the cupper with similar focused laser intensity. The figure shows the temporal profiles of the signals with an expanded scale of the first 400 μs range. Both temporal profile and the amplitude of the signal are almost identical to each other.

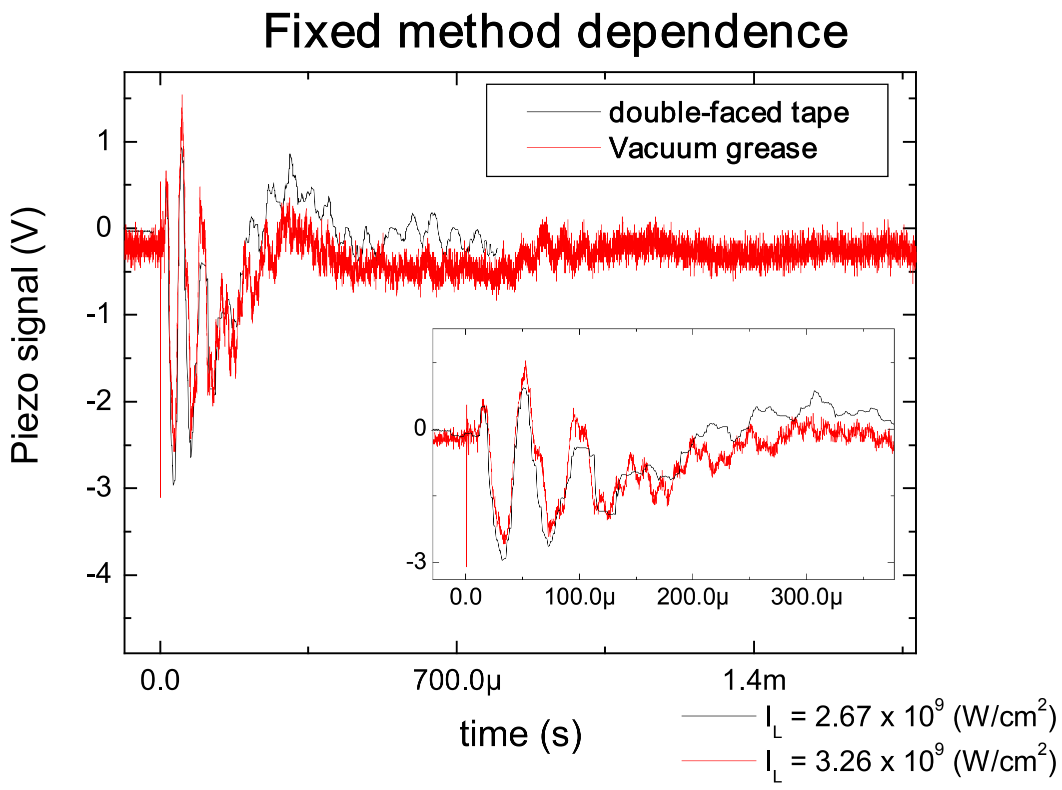


Figure 4 Effects of interfacing methods between cupper plate and piezo electric plate

Confirmation of good absorption in the materials

It is confirmed that all the materials tested the experiments have strong absorption against 10.6 μm radiation. Experimental setup is shown in Figure 5where liquid was place on a polyethylene sheet that is transparent (86% transmission) to 10.6 μm radiation. The thickness of the liquid on the sheet is about 1 mm for all the liquid. Laser pulse incident from polyethylene sheet and whose transmission is measured by an energy meter above. Incident pulse energy was 860 mJ. Practically no energies transmit through any of the liquid.

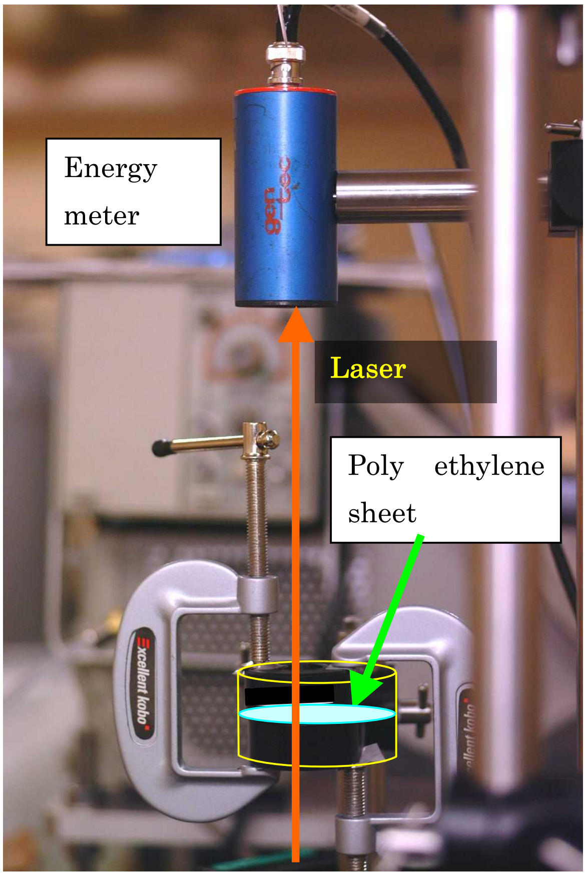


Figure 5 Experimental setup for absorption measurement

Experiment with water layer

To show the significance of using liquid propellant over pure ablation, thrust generated by laser irradiation on water surface was measured. Figure 6 shows the comparison of thrust generated from cupper surface and cupper covered with a thin water layer. Thrust generated from the water covered cupper surface is about 5.5 times larger than that of from bare cupper plate.

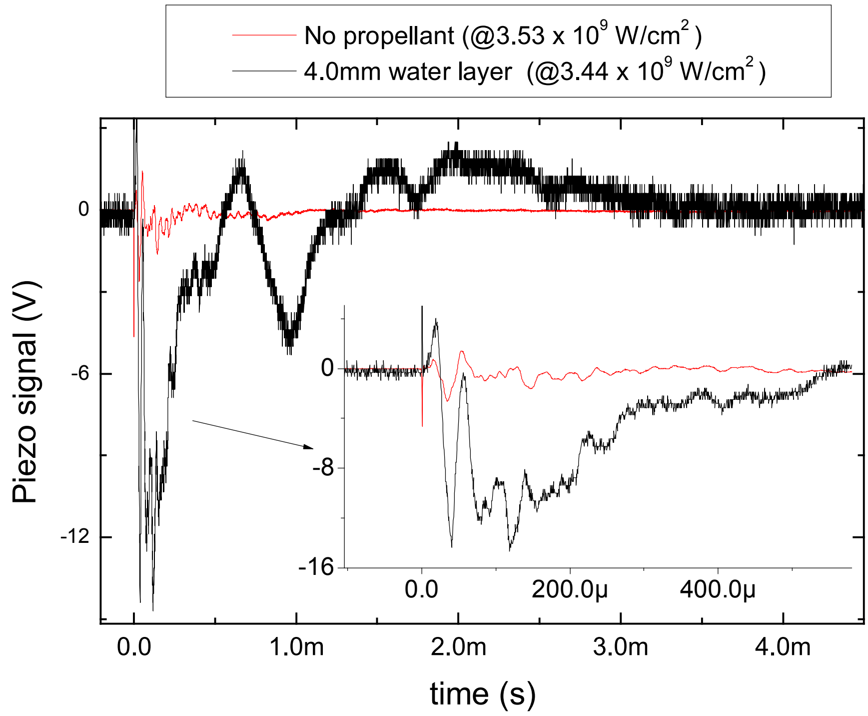


Figure 6 Comparison of thrust generation with and without water layer on a cupper plate

Thrust dependence on irradiated laser intensity was measured with bare cupper plate. Thrust from water covered ¥cupper plate is plotted as a comparison. Two variations of water layer thickness were chosen, 0.9 mm and 2.1 mm. Laser intensity was altered by changing focal spot size while pulse energy been kept constant. The results are shown in Figure 7. Thrust from bare cupper plate shows no dependence on laser intensity.

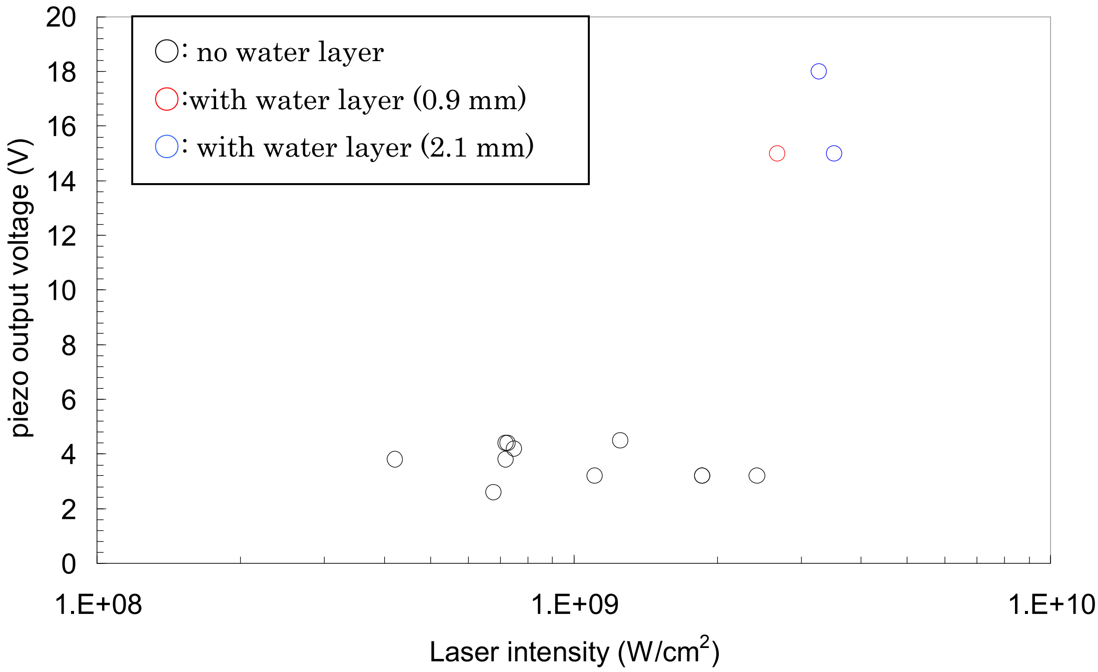


Figure 7 Thrust dependence on laser intensity on bare cupper plate

Water thickness effects

Cupper plate covered with various thick water layer was irradiated to see the thrust dependence on layer thickness. The thickness of the water ware varied from 0.9 mm to 4.8 mm. The focused laser intensity was kept about $3*10^9$ W/cm^2. The peak and temporal profile of impulse seem dependent on the thickness of the water layer as shown in Figure 8.

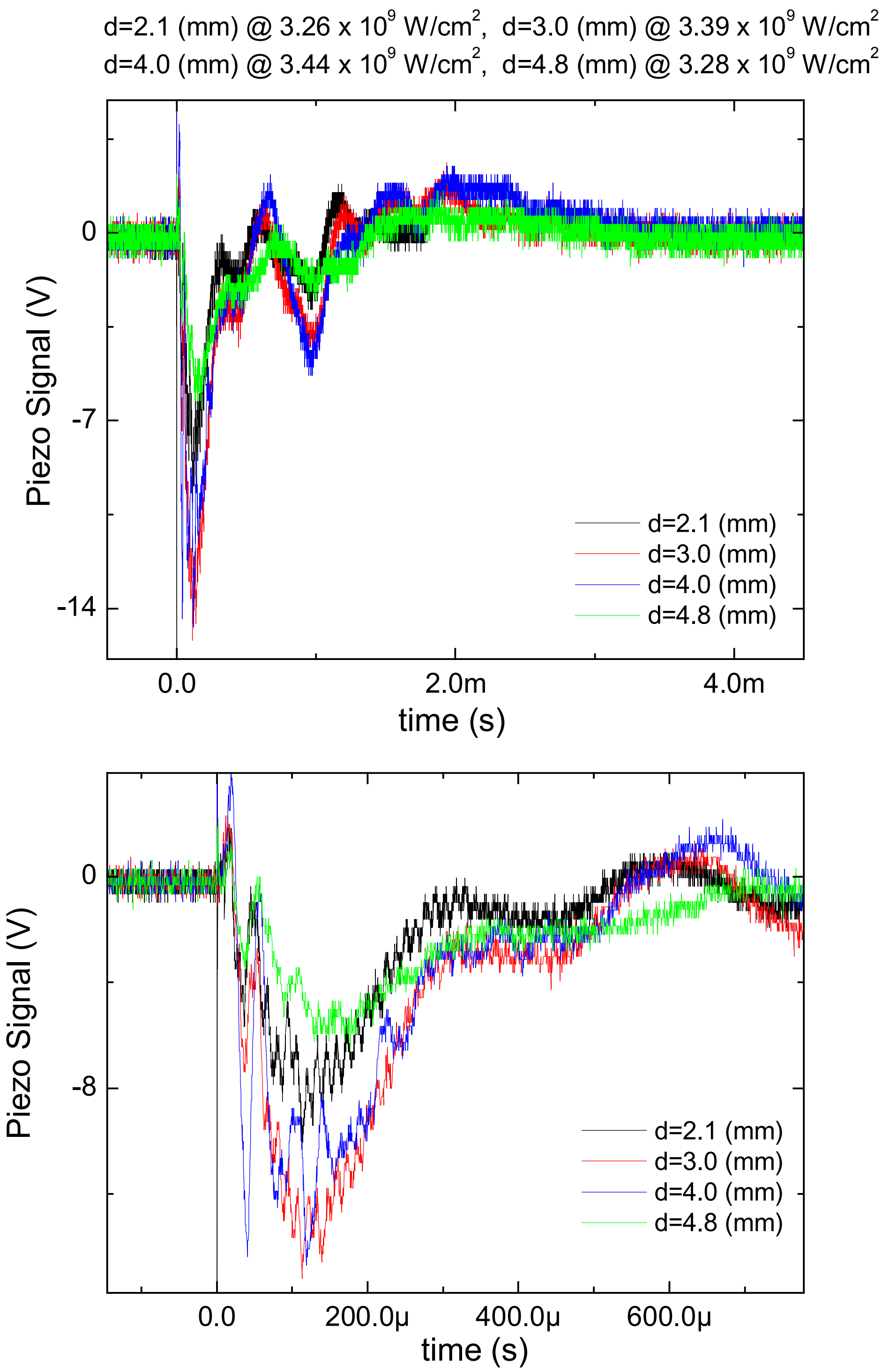


Figure 8 Temporal profile of thrust generated on various thick ness of water

(The lower figure is the expansion of the above)

To see the phenomenon, the peak values of the impulse for each thickness are plotted in Figure 9. Data points indicated by crosses and open circles correspond to impulse measured with cupper plate fixed by the sticky tape and vacuum grease respectively. Impulse measure with sticky tape is larger than one with vacuum grease. Laser intensity dependence shows that the optimum water thickness is 4 mm.

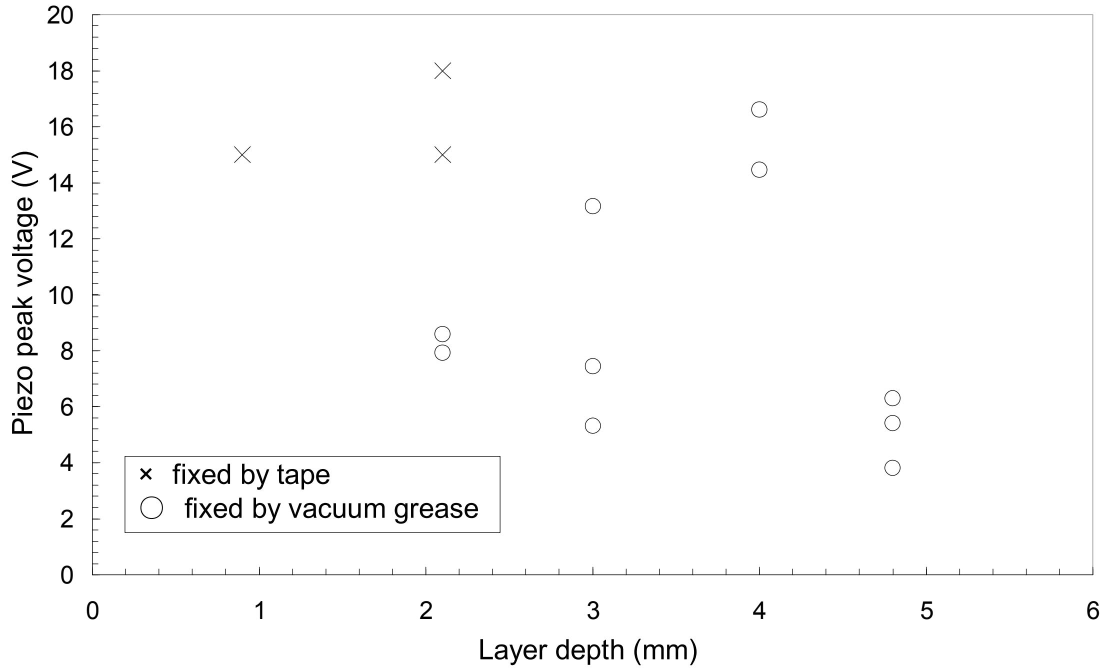


Figure 9 Water layer dependence of impulse peak value

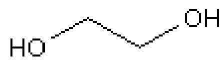
Liquid dependence

Four kinds of liquid propellant were chosen for the experiments, water, ethylene glycol, caster oil and diethyl ether. Basic properties of these materials are listed in Table 1. These materials are chosen so that various values of viscosity will be tested for the proposed feeding system. The dynamic viscosity of the propellant is listed below,

Dynamic viscosity [in cP: centi Poise]

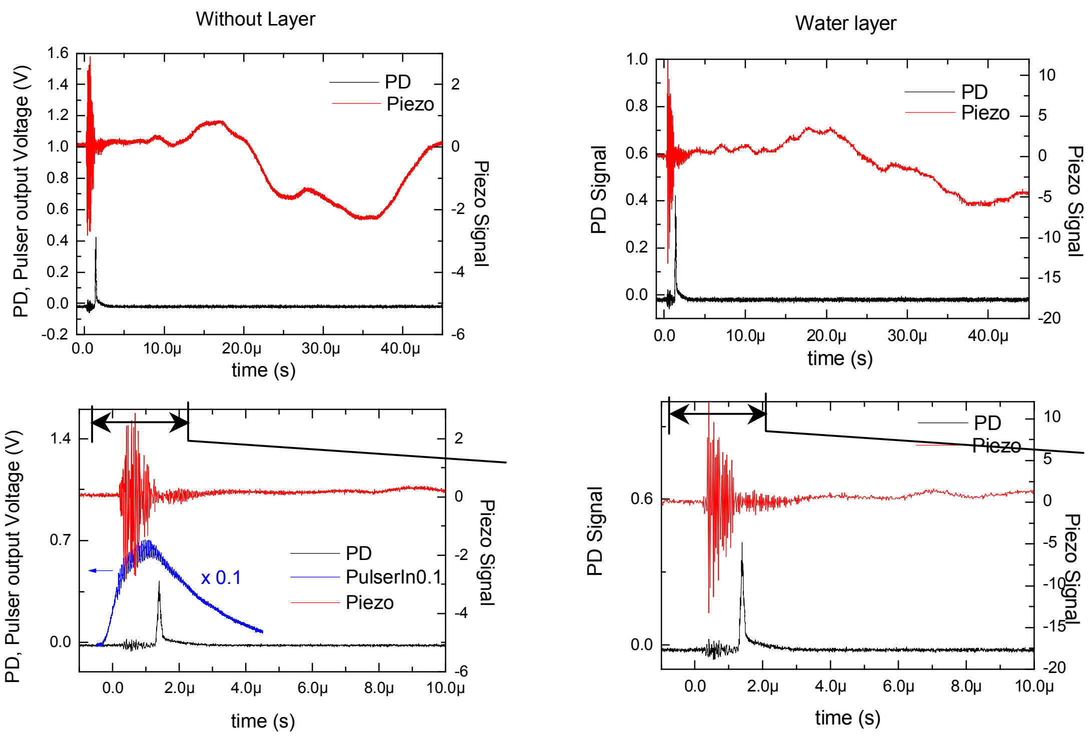
Diethyl ether:	0.233
Water:	1.002
Ethylene glycol:	19.9
Caster oil:	985

Table 1 Basic properties of propellant used in the experiments

Water • **Formula:** H_2O • **Molecular Weight:** 18.02 • **CAS Registry Number:** 7732-18-5 	Ethylene Glycol • **Formula:** $C_2H_6O_2$ • **Molecular Weight:** 62.07 • **CAS Registry Number:** 107-21-1 • **Chemical Structure:** 
Caster Oil • **Formula:** $C_{18}H_{34}O_3$ • **Molecular Weight:** 298.46 • **CAS Registry Number:** 8001-79-4 • **Chemical Structure:**	Diethyl Ether • **Formula:** $C_4H_{10}O$ • **Molecular Weight:** 74.12 • **CAS Registry Number:** 60-29-7 • **Chemical Structure:** 

Time scale of impulse generation

To see dynamic behavior of liquid propellant irradiated by a nano second laser pulse, absolute temporal profiles after laser irradiation was measured. One of the split laser beam was directed to a photon drag detector in order to record the exact timing of laser irradiation. The onset timing of the impulse was defined to be -1 V and was measured to be 26 μs from the laser irradiation timing. Figure 10 shows the temporal profile of impulse generated on water covered target. This timing is two to three orders of magnitude slower than that of laser ablation[1].



Trigger timing is indicated by PulserIn 信号

Figure 10 Onset timing of impulse from water covered target

Temporal profiles of impulse were measured with various conditions; changing liquid layer thickness while keeping laser focal intensity constant and vice versa. For layer thickness dependence, laser intensity was kept at $3.4*10^9$ W/cm^2. For intensity dependence, the values of layer thickness were 0.1, 0.9, 0.9 and 4.8 mm for water, ethylene glycol, caster oil and diethyl ether, respectively. Only 4.8 mm thick diethyl ether was possible due to rapid vaporization. For the same reason, only laser intensity dependence was possible. The results are shown in Figure 11 and Figure 12.

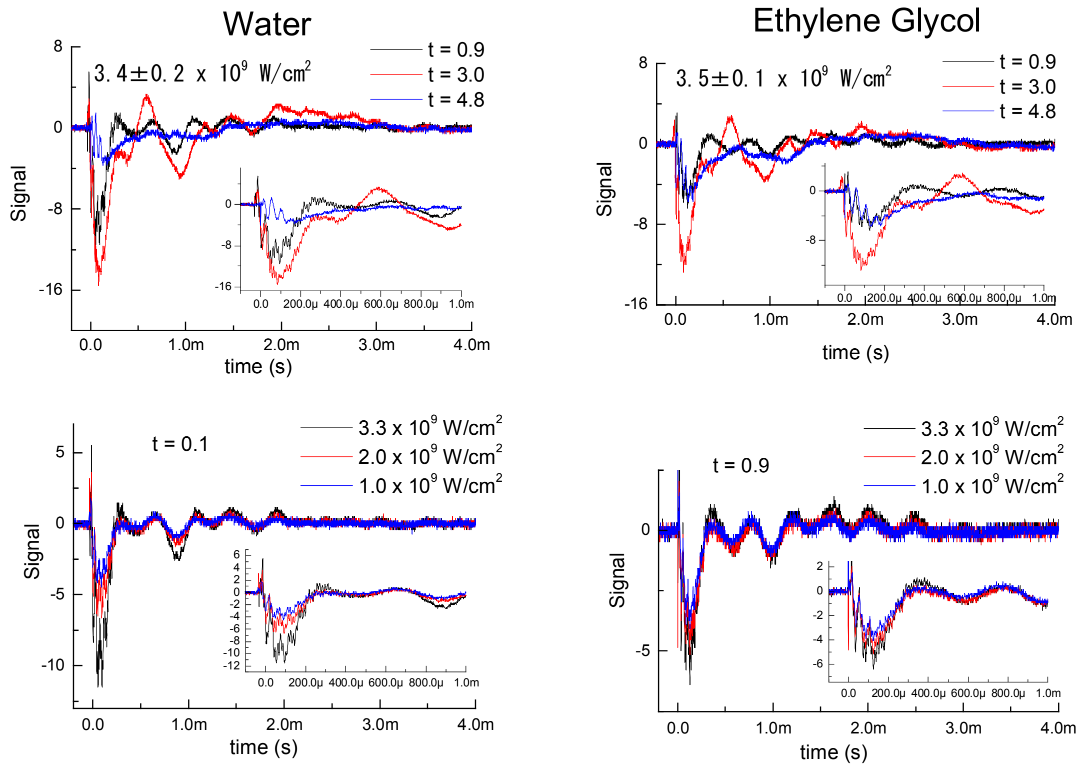


Figure 11 Temporal profile for case of water and ethylene glycol

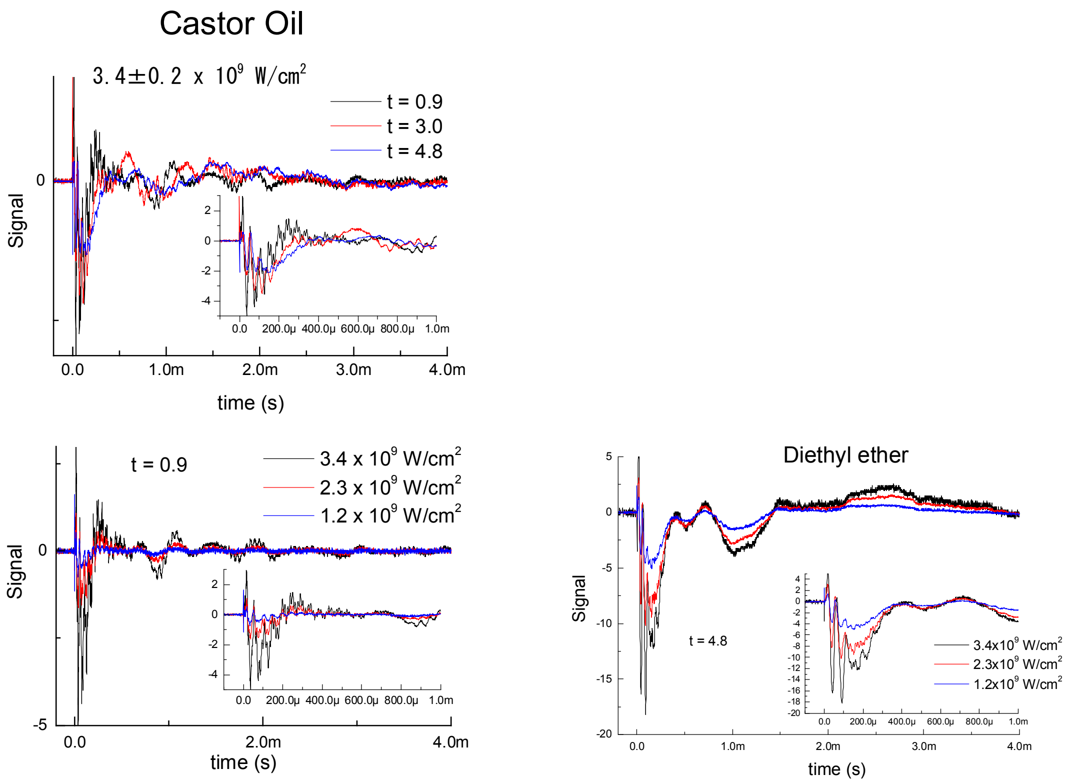


Figure 12 Temporal profile for case of caster oil and diethyl ether

Thickness dependence shows that longer periods of impulse are observed with thicker liquid layer.

Laser intensity dependence shows that higher intensity gives larger impulse. From these results, laser intensity and propellant thickness dependence of momentum coupling coefficients, C_m can be calculated.

Momentum coupling coefficient

Water

Figure 13 and Figure 14 show the laser intensity and propellant thickness dependence of C_m. No significant dependence on laser intensity is seen in the parameter range. The propellant thickness dependence on the other hand shows moderate dependence and the 3-mm thick propellant gives the largest C_m. A similar result has been obtained by Yabe[2].

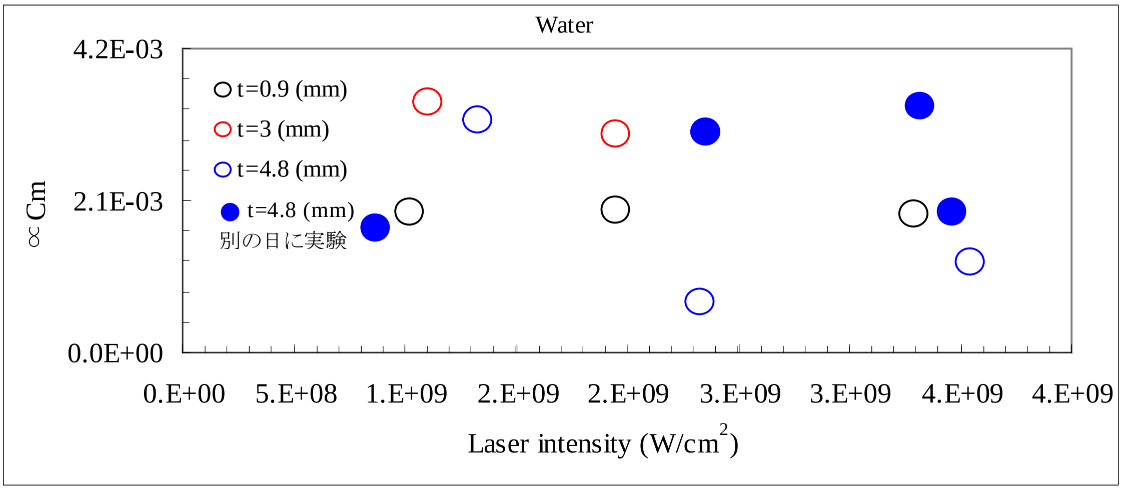


Figure 13 Laser intensity dependence of momentum coupling coefficient, C_m

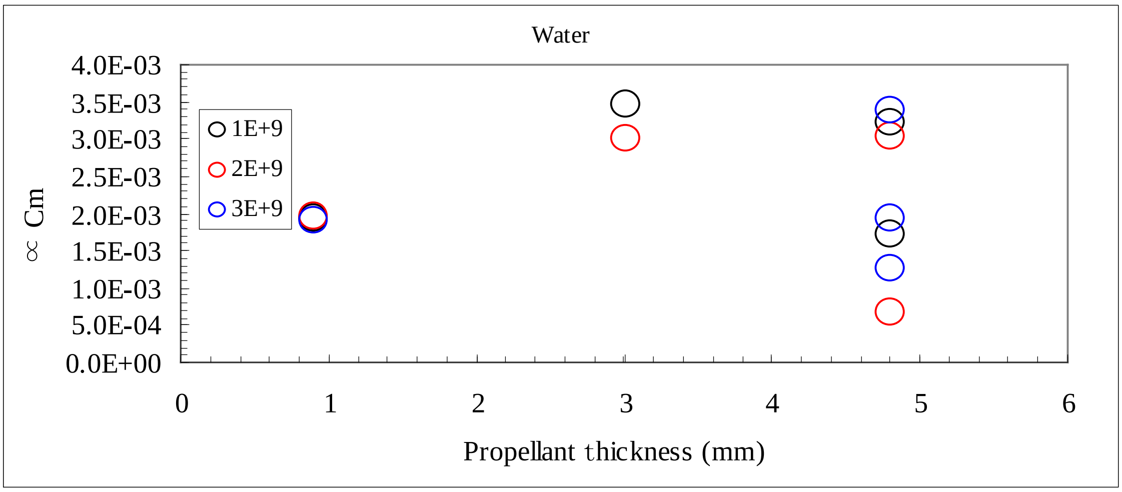


Figure 14 Propellant thickness dependence of momentum coupling coefficient, C_m

Ethylene Glycol

No significant laser intensity dependence was observed, however propellant thickness dependence looks similar with the case of water propellant.

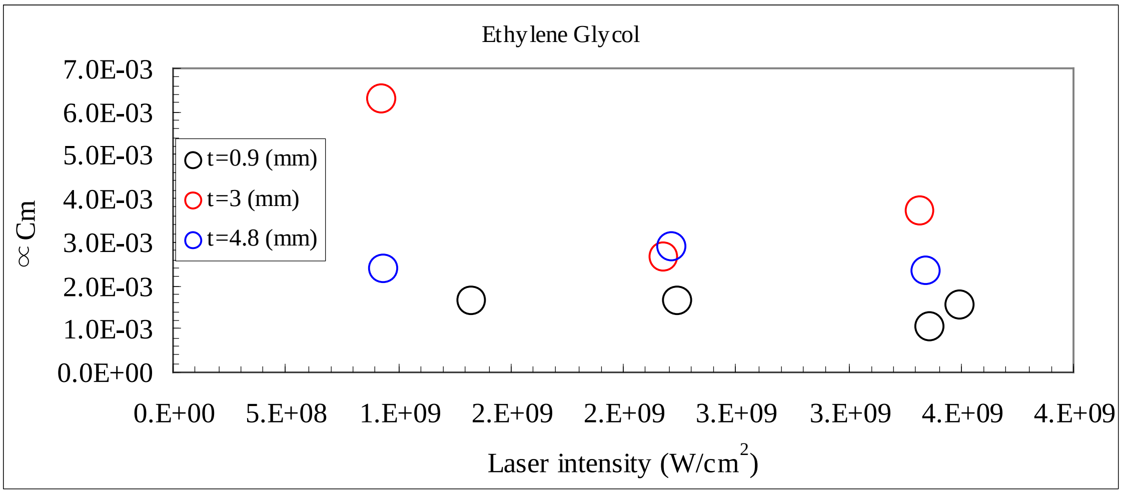


Figure 15 Laser intensity dependence of momentum coupling coefficient, C_m

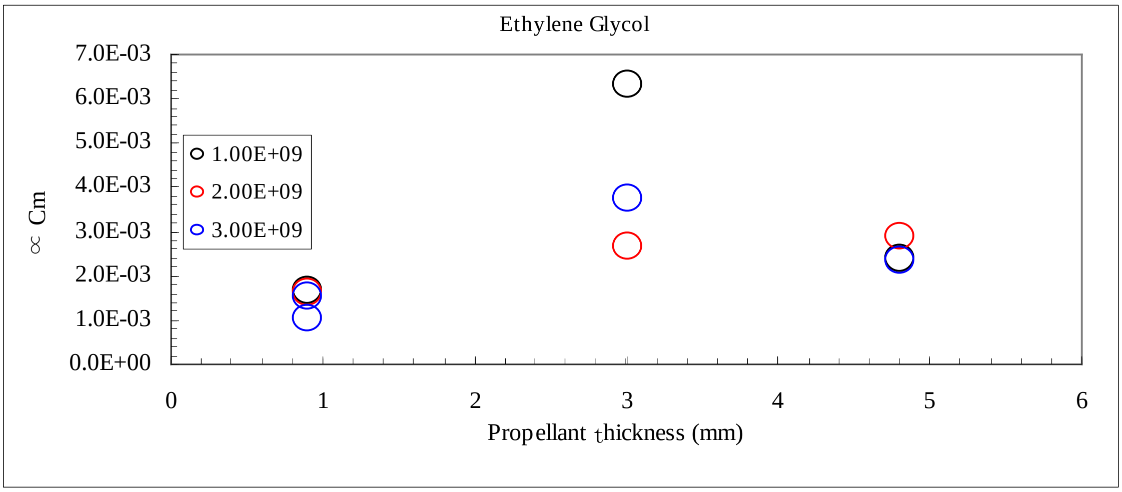


Figure 16 Propellant thickness dependence of momentum coupling coefficient, C_m

Caster oil

There is rather clear dependence on laser intensity. However, propellant thickness does not show dependence.

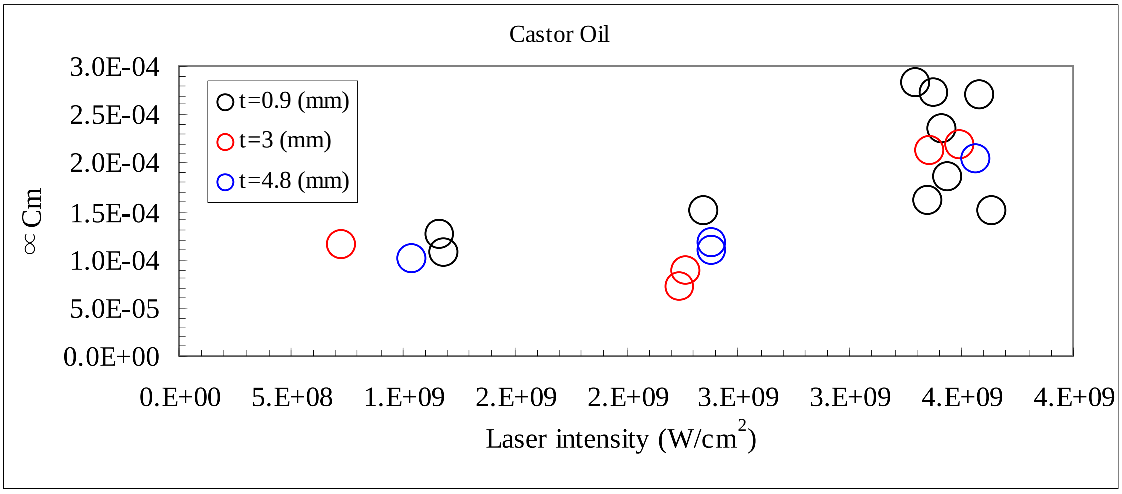


Figure 17 Laser intensity dependence of momentum coupling coefficient, C_m

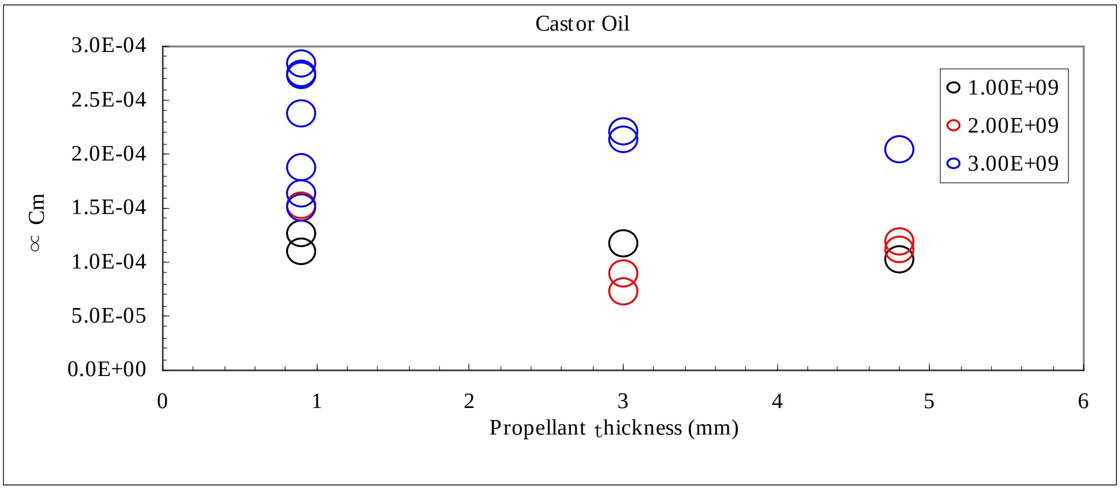


Figure 18 Propellant thickness dependence of momentum coupling coefficient, C_m

Diethyl ether

Since diethyl ether is highly volatile, only data with 4.8-mm thick was obtained. This material shows the highest C_m among the tested propellant.

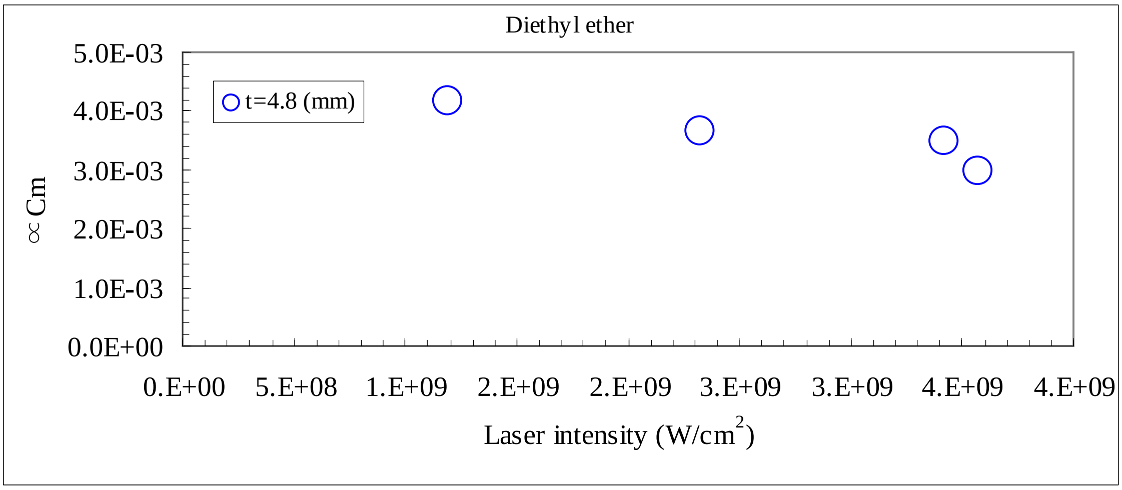


Figure 19 Laser intensity dependence of momentum coupling coefficient, C_m

Material dependence of momentum coupling coefficient

Figure 20 summarizes the laser intensity dependence of Cm with the kind of material as a parameter. It is seen that diethyl ether exhibits slightly higher C_m. On the other hand, caster oil shows the lowest C_m.

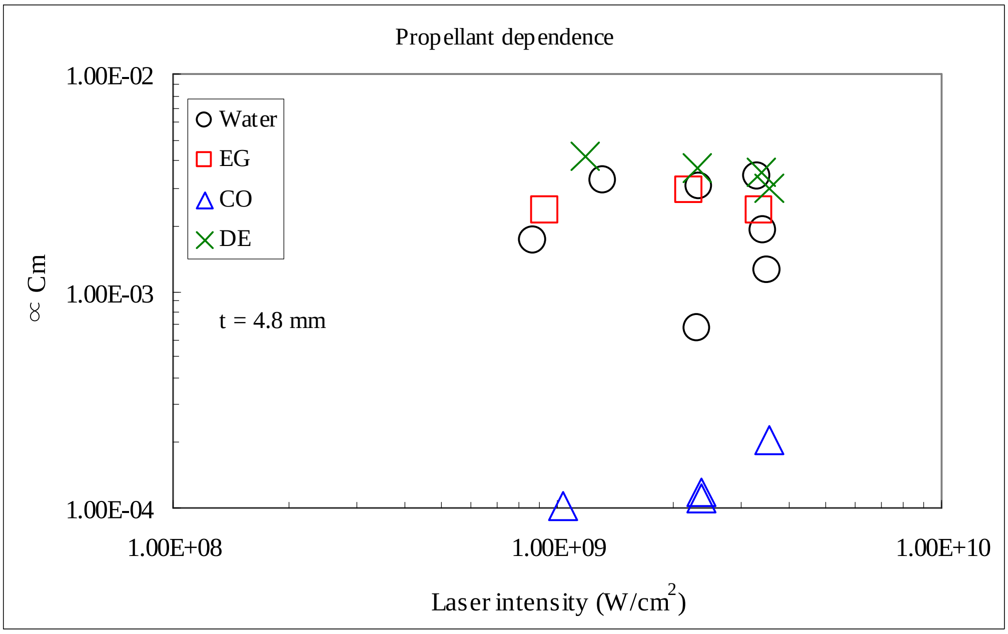


Figure 20 Summary of momentum coupling coefficient dependence on laser intensity

Propellant expansion imaging

Figure 21 is instantaneous image of propellant expansion taken with a high speed camera. The shutter speed and timing are 1 ms and 100 μs respectively. Again the

appearance of expansion seems correlated with material viscosity. Water and ethylene glycol show similar expansion image while intensity of propellant expansion is the largest with diethyl ether leading to the highest C_m. Caster oil, on the other hand, only generates expansion of mist and mass is significantly less than other materials. These observations seem well correlated with material dependence of C_m as is described in the previous section.

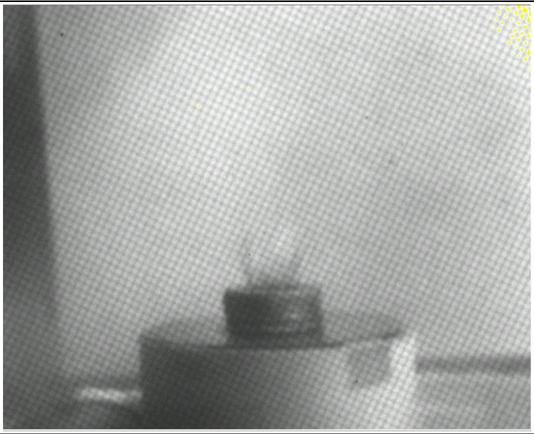
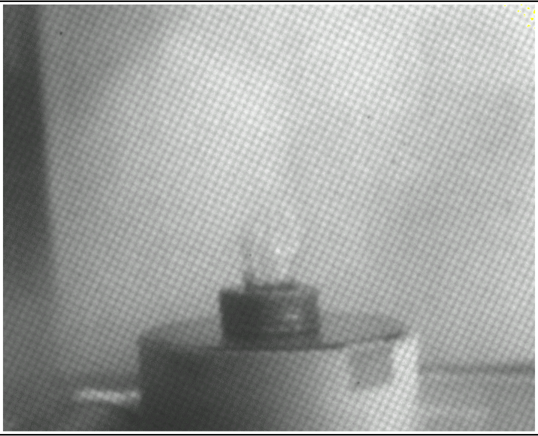
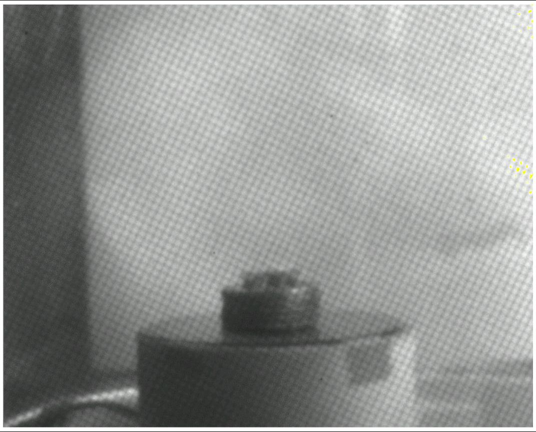
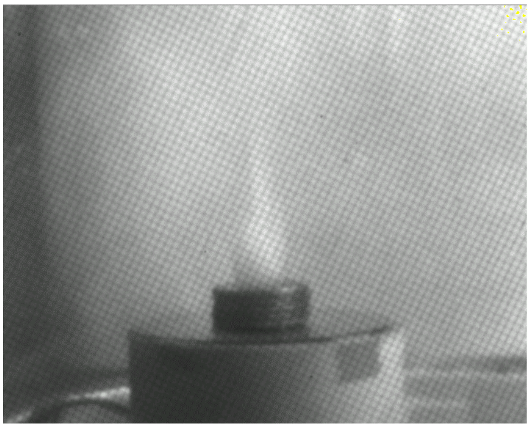
	
Water Thickness=4.8mm、I_{laser}=3.5x10^{9} W/cm^{2}	EG Thickness=4.8mm、I_{laser}=3.3x10^{9} W/cm^{2}
	
CO Thickness =4.8mm、I_{laser}=3.6x10^{9} W/cm^{2}	DE Thickness =4.8mm、I_{laser}=3.4x10^{9} W/cm^{2}

Figure 21 Instantaneous image of propellant expansion

Liquid propellant feeding characterization

Experimental setup

Characterization of flow rate dependence on backing pressure was measured using an experimental setup shown in Figure 22.

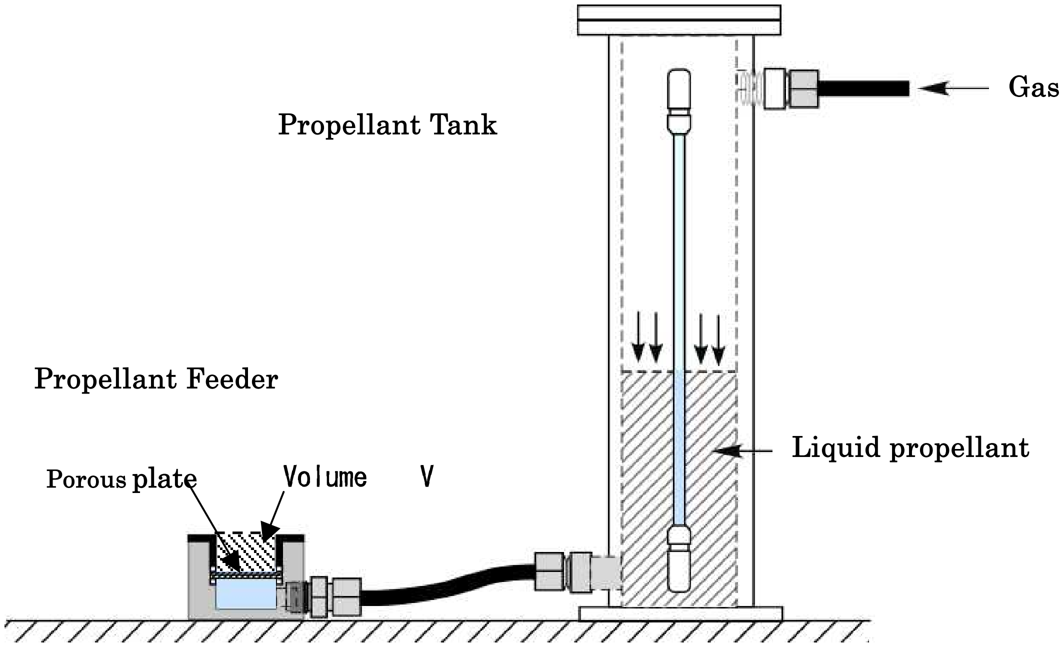


Figure 22 Experimental setup for porous material characterization

Four kinds of liquid, diethyl ether, water, ethylene glycol and caster oil were charged in a pressurized tank and pushed by nitrogen gas. The pressure was controlled by gas regulator and fast response electromagnetic valve. Amount of the liquid, V [mℓ] fed through a plate made of porous materials is measured with possible combination of the liquid and porous materials. The flow rate, u [mℓ/s/cm^2] is related to the measurable parameters shown in the figure,

$$u = \frac{V}{tS}$$

where t, S are time interval of "pushing" and the cross section of the porous plate. The pressure of the nitrogen gas was varied from 0.1 to 0.7 MPa. The effect of hydraulic head due to the difference in the height of the liquid surface inside the tank and the porous plate was neglected since the pressure of the nitrogen is two orders of magnitude larger than the effect. Five measurements were executed to minimize any measurement error in timing.

In these experiments, porous stainless steel plates were used as a liquid feeding plate. Their degree of "easy to be penetrated" is characterized by "porosity", that is defined by a ratio of non-solid volume to the total volume of material. The values of porosity tested in the experiments were 0.2, 0.5, 1.0, 2.0, 10, 20, 40.

Additional properties of the tested liquid are listed in Table 2. The pictures of the

setup and porous plates are shown in .

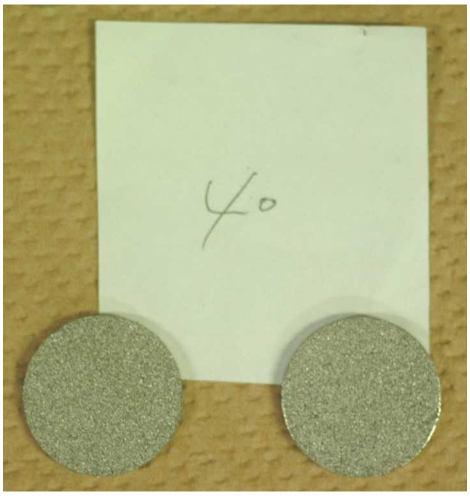
Table 2 Hydraulic property of tested liquid

Material	Viscosity@25℃ (Pa･s)	Density (g/cm^3)	Remarks
Diethyl Ether	0.224	0.71	T_{fus}=-116.3℃、T_{boil}=34.48℃
Water	0.890	1	T_{fus}=0℃、T_{boil}=100℃
Ethylen Glycol	17.33	1.12	T_{fus}=-12.6 ℃ 、 T_{boil}=197.85 ℃ 、 Water solvable
Caster Oil	700	0.96~0.97	

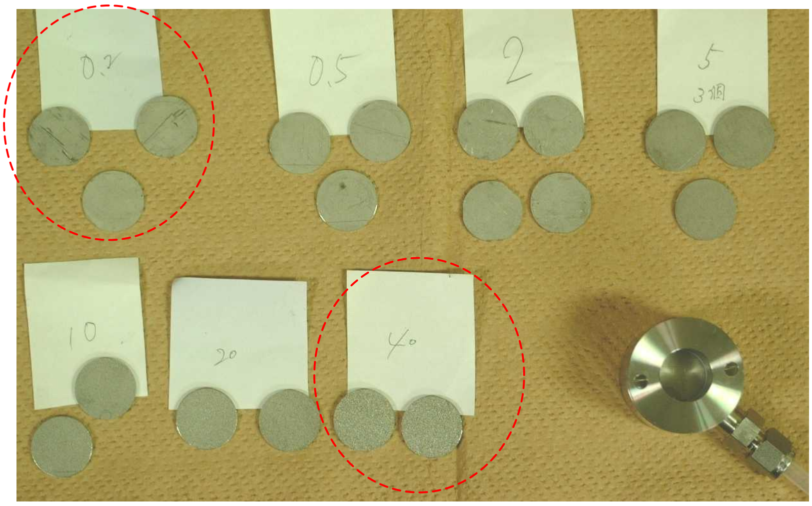
Propellant feeder＆Tank

Propellant feeder

Porous plate, porosity / 0.2



Porous plate, porosity / 40



Porous plate and propellant feeder

Figure 23 Experimental setup and porous plates

Since the viscosity of ethylene glycol and caster oil is very high, any residual liquid in the feeder can not be removed by itself and special arrangements in the liquid feeder was necessary. The schematic of the arrangements is depicted in Figure 24. Two electric valves are equipped for gas feeding and leak. Additional rotary vacuum pump is connected to suck highly viscous liquid.

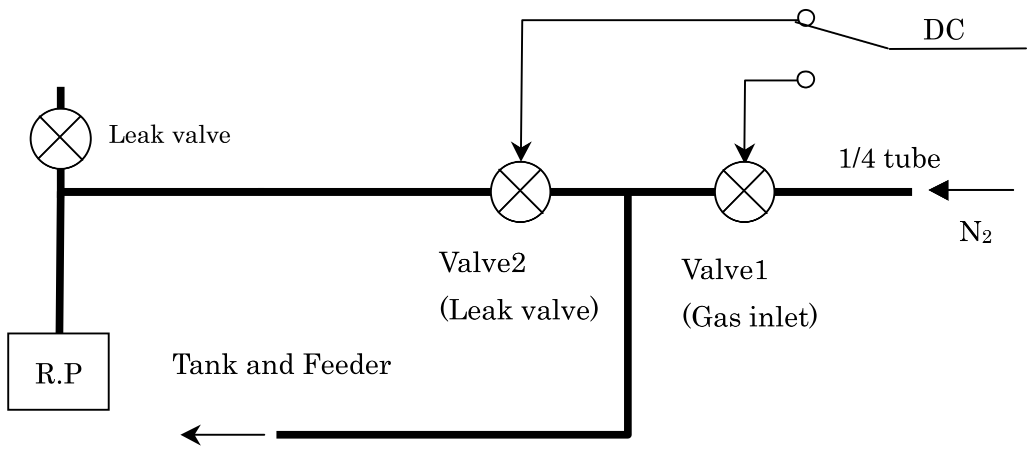


Figure 24 Feeder cleaning system

Results

In Figure 25 through Figure 28, flow rates are plotted as a function of backing pressure with different porosity. With some conditions flow rates are too fast or too slow and are not plotted.

With given porosity of the porous materials, the flow rate linearly depends on the

backing pressure.　Linear fitting for each condition is shown in the plot.

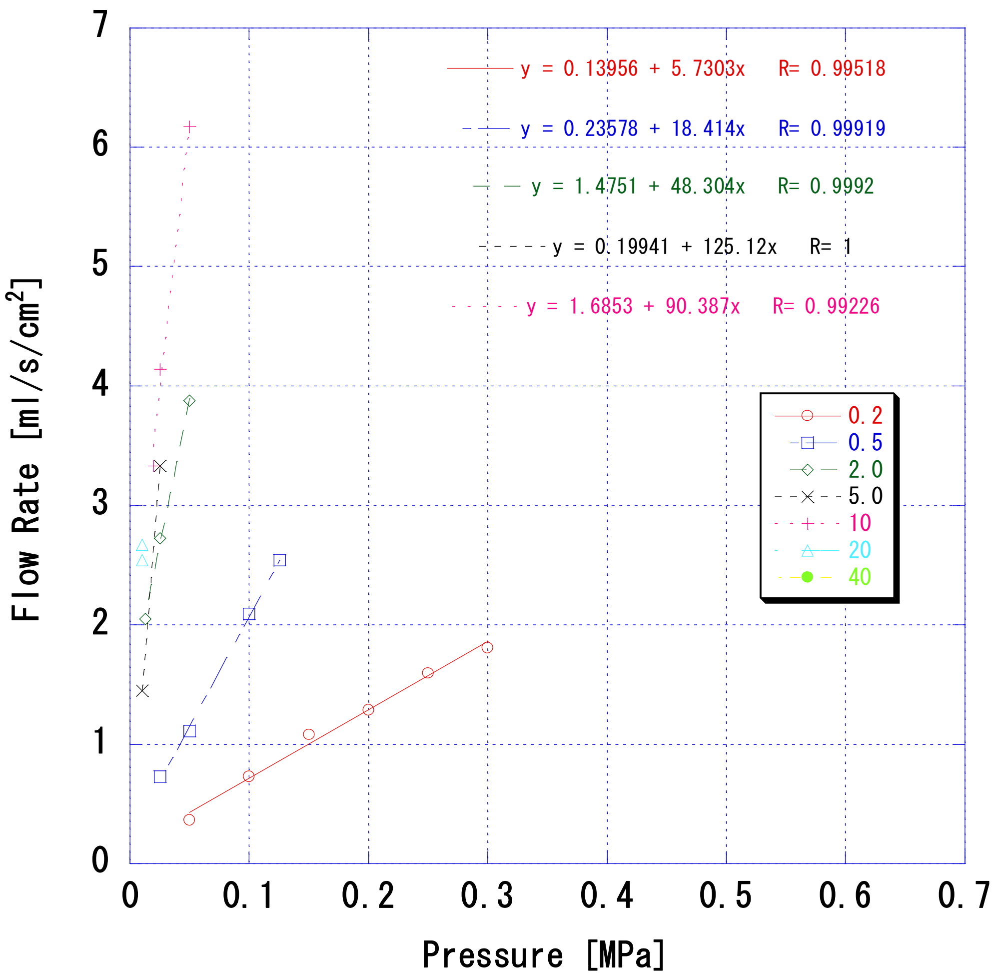


Figure 25 Flow rate as a function of backing pressure with porosity as a parameter (Diethyl ether)

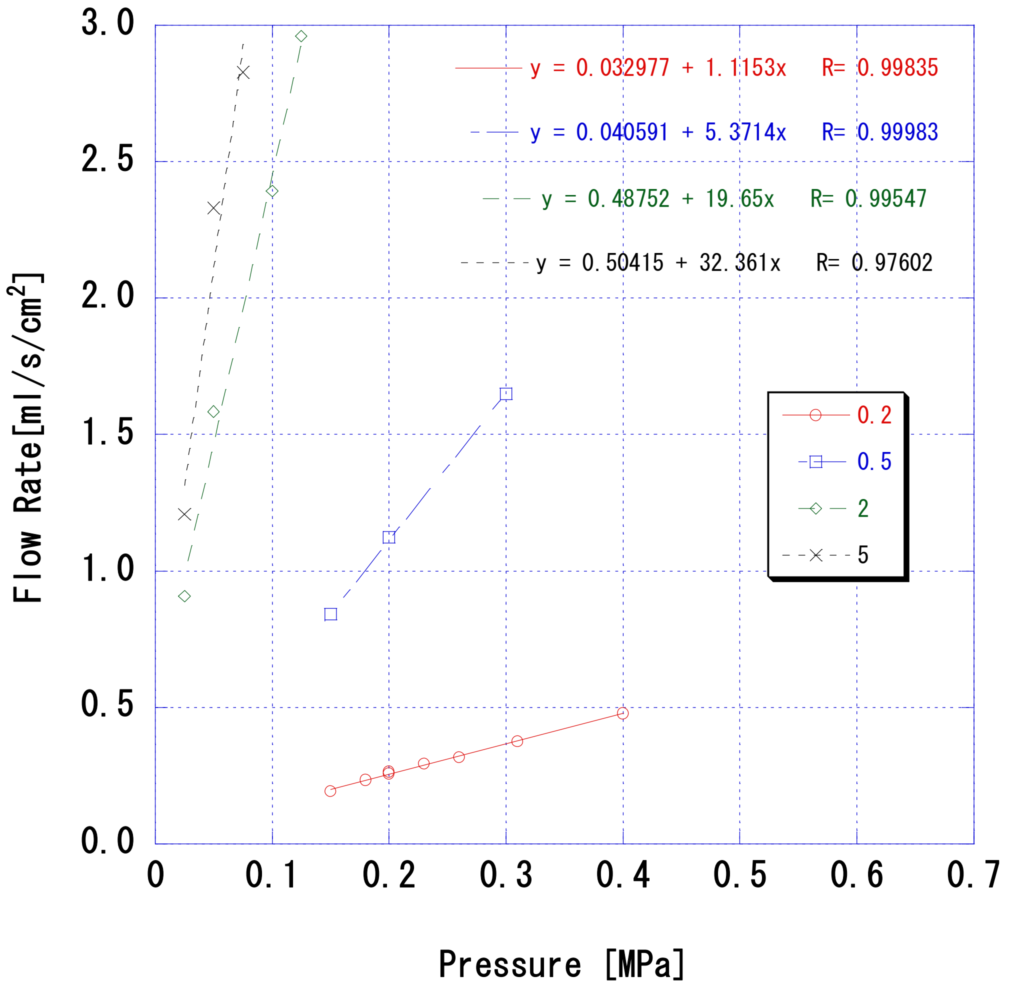


Figure 26 Flow rate as a function of backing pressure with porosity as a parameter (Water)

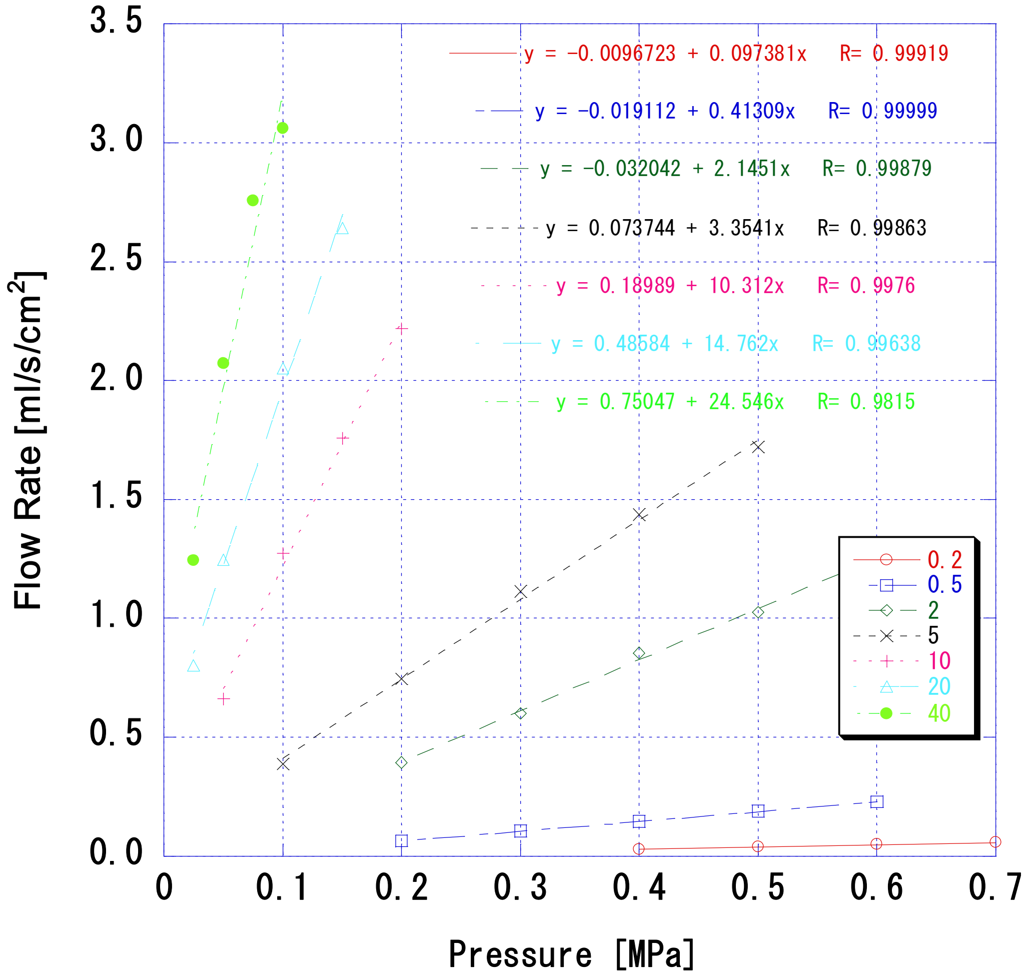


Figure 27 Flow rate as a function of backing pressure with porosity as a parameter (Ethylene Glycol)

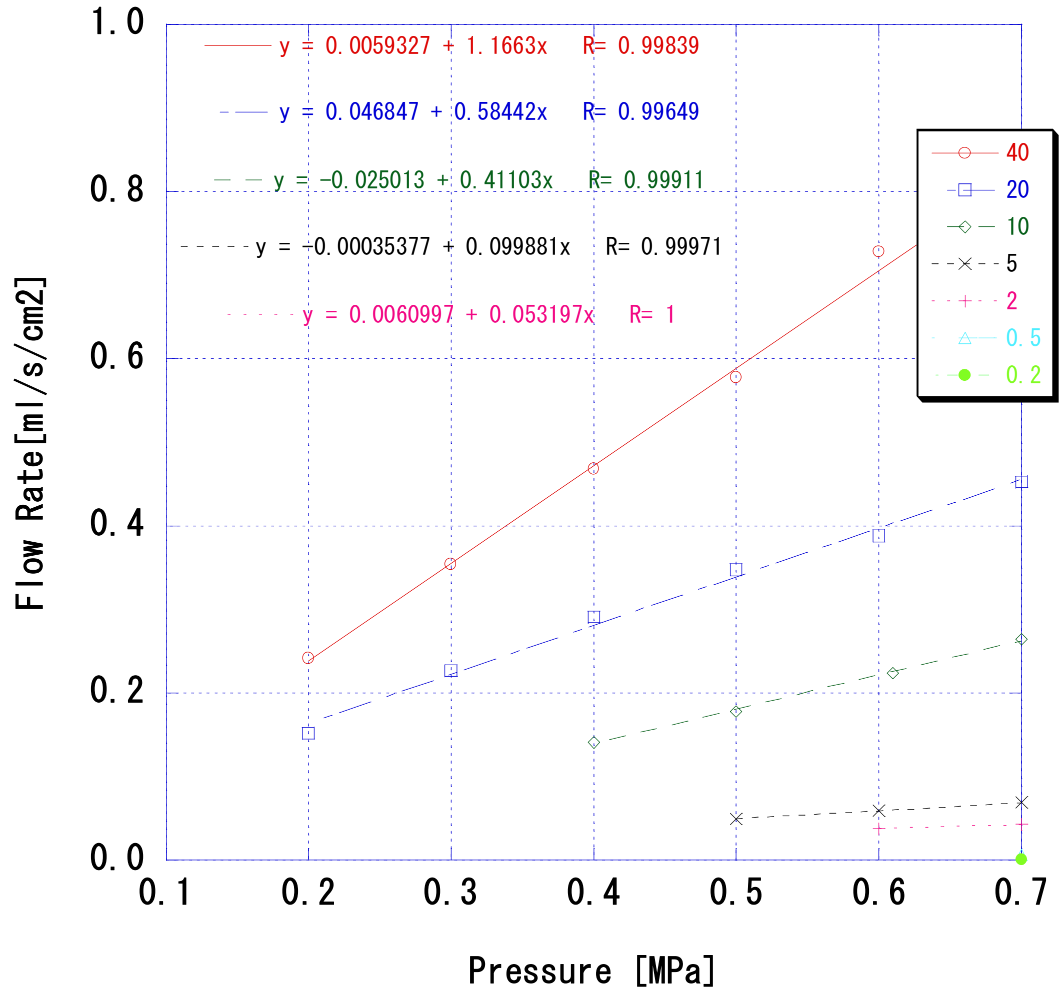


Figure 28 Flow rate as a function of backing pressure with porosity as a parameter

(Caster Oil)

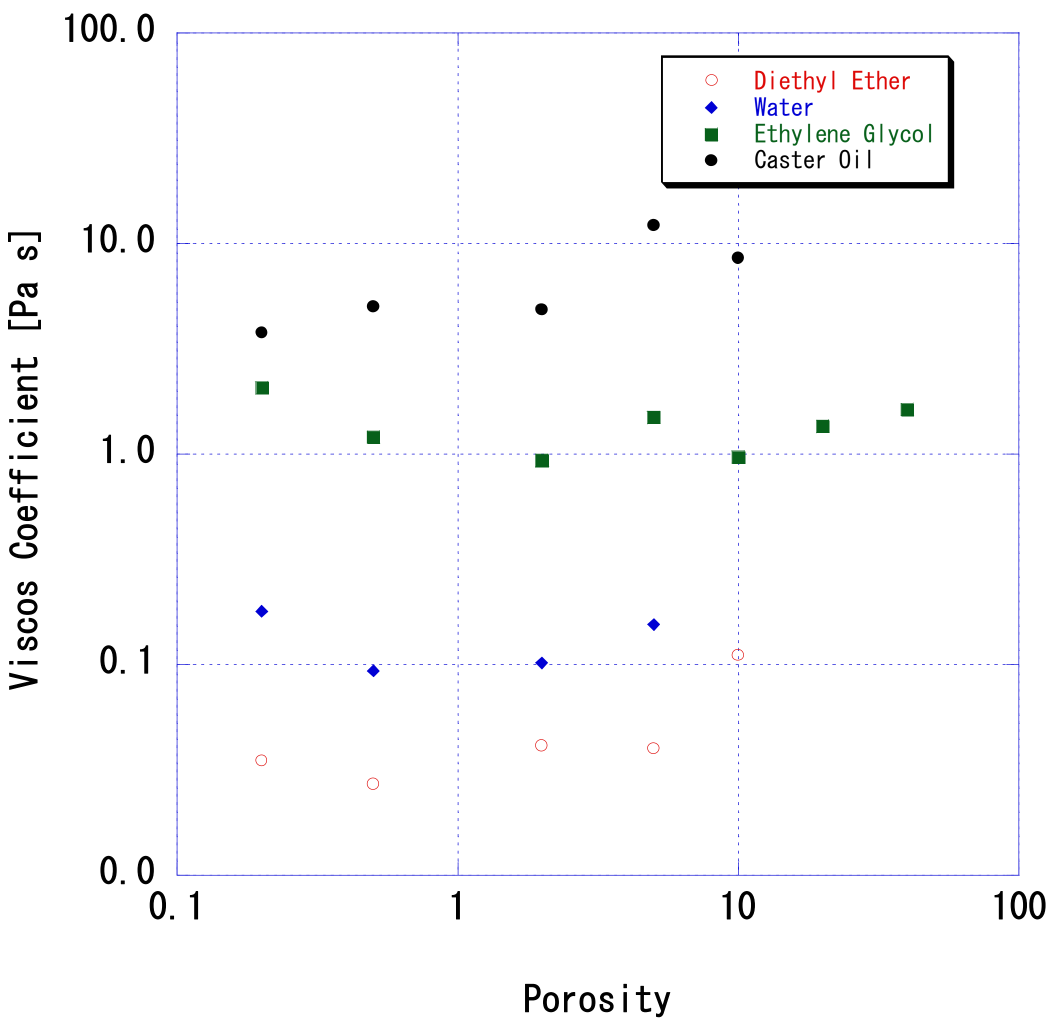
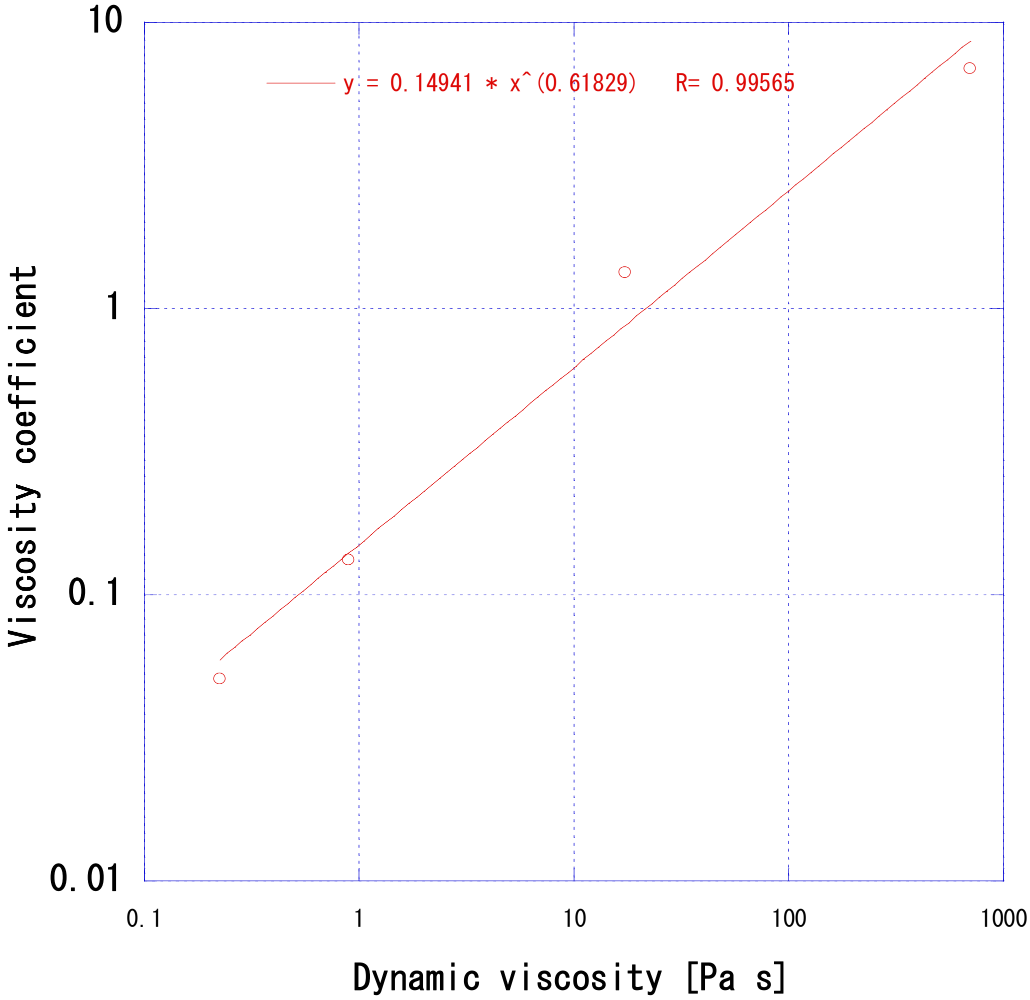


Figure 29 Viscous coefficients of various materials

From Darcy's Law, flow rate is supposed to linearly depend on backing pressure with $\alpha = \kappa / \mu$ is a proportional constant, where κ and μ are permeability of a porous plate and dynamic viscosity of the liquid, respectively. Since α is determined by the experiments, we can calculate expected dynamic viscosity, $\mu = \kappa / \alpha$ that is plotted as a function of porosity. Porosity of each material is constant within a factor of two over a wide range of porosity of two to three orders of magnitude.

As is expected from Darcy's Law, viscous coefficient should be correlated with dynamic viscosity that is shown in Figre 30. However the correlation is weaker than linear, about 0.6^{th} power to the dynamic viscosity.



Figre 30 Correlation between Dynamic viscosity and viscosity coefficient

Discussion

No dependence on interfacing materials for thrust generation from bare cupper plate: Impulse generated from bare cupper plate is expected to be very short in time, probably in the range of few nanoseconds. The short phenomenon can not be followed by the interfacing material such as grease and sticky tape. The short impulse from the cupper plate sees "hard" layer of such interface while transverse them. These layers act as rigid solid material rather than soft and viscous layers therefore, force exerted on the piezo plate exhibits no significant dependence on the materials. In the case with liquid layer on the cupper plate, on the other hand the impulse generated by laser pulse is first converted to the motion of the surface liquid whose time scale is an order of hydrodynamic motion that can be followed by the interfacing materials. The sticky

tape does not allow share motion while vacuum grease does. Therefore, thrust measured through the sticky tape is larger than one with vacuum grease.

Time scale of onset of impulse through liquid layer: The delay of impulse onset through liquid layer is probably due to the transverse time of shock wave across the liquid propellant.

Liquid layer thickness dependence: As the thickness of the liquid layer increases, the radius of the shock wave reaching the surface of the cupper layer becomes larger leading to a longer period of impact. In fact, in the case of impact generated by a sphere hitting on the surface of a plate, the impact period, τ [s] is a function of the diameter of the sphere, D [m]. [3]

$\tau = 0.0043D.$

Only caster oil shows laser intensity dependence of C_m: Caster oil has the highest viscosity among the tested liquid. Amount of mass splashed by laser pulse is the smallest and thus exhibits the smallest C_m among the tested materials. It is expected that in the case of liquid with low viscosity, entire thickness of the liquid explodes with the present intensity range and that value of C_m saturates. This saturation can explain the very weak intensity dependence of the C_m as well as rather large data. Spread. It is also seen that the highest C_m is observed with diethyl ether propellant that has the lowest viscosity.

However, the lowest C_m of caster oil does not mean high specific impulse, I_{sp}, since the low C_m might be due to very low mass consumption. Isp with caster oil will have to be measured in a separate experiment.

From the above discussion, there is an optimizing condition for viscosity in terms of C_m and propellant feeding system. For example, when water is chosen as propellant, the optimum thickness of the layer is about three millimeter. To satisfy this condition, feeding rate, R_{flw} and pulse repetition rate, f_{rep} have to be matched in a following manner,

$$T_{opt} = \frac{R_{flw}}{f_{rep}}$$

where T_{opt} is the optimum propellant thickness. IN the case of water propellant, this condition can be satisfies when f_{rep} is set to be in the order of 10 Hz. Less than 0.1 Mpa is required for this operating condition and might be provided by water vapor pressure through the porous plate.

Summary

It can be concluded that use of porous plate for feeding liquid propellant is possible. Several operating and designing parameters such as porosity, feeding pressure, propellant viscosity and vapor pressure, laser pulse repetition rate have to be optimized for the best performance of the system. Matching of the laser wavelength and absorption coefficient of propellant is also an important factor. It was found that realistic choice of these parameters is possible within reasonable range of physical value.

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